

Prospects in Eta Decays at JEF

Liping Gan

University of North Carolina Wilmington

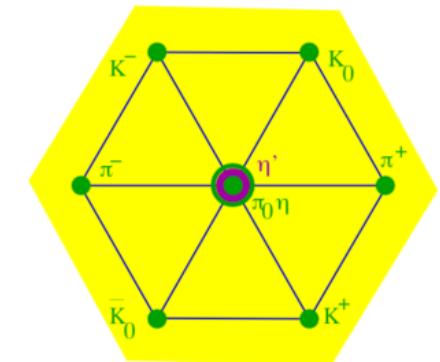
Outline

1. Introduction to the JEF experiment
 - Physics motivation
 - Experimental approach
 - Physics objectives and sensitivities
2. Current status
3. Summary

Why η is a unique probe for QCD and BSM physics?

- ◆ A Goldstone boson due to spontaneous breaking of QCD chiral symmetry

→ η is one of key mesons bridging our understanding of low-energy hadron dynamics and underlying QCD



- ◆ All its possible strong and EM decays are forbidden in the lowest order so that η has narrow decay width ($\Gamma_\eta = 1.3 \text{ KeV}$ compared to $\Gamma_\omega = 8.5 \text{ MeV}$)
→ Enhance the higher order contributions (by a factor of ~ 7000 compared to ω decays). Sensitive to weakly interacting forces.

- ◆ Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
→ tests for C, CP

- ◆ All its additive quantum numbers are zero and its decays are flavor-conserving
→ effectively free of SM backgrounds for new physics search.

Rich η and η' Physics

Channel	Expt. branching ratio	Discussion
$\eta \rightarrow 2\gamma$	39.41(20)%	chiral anomaly, $\eta-\eta'$ mixing
$\eta \rightarrow 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \rightarrow \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χ PT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \rightarrow \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χ PT, axion-like particles (ALPs)
$\eta \rightarrow 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [54]
$\eta \rightarrow \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
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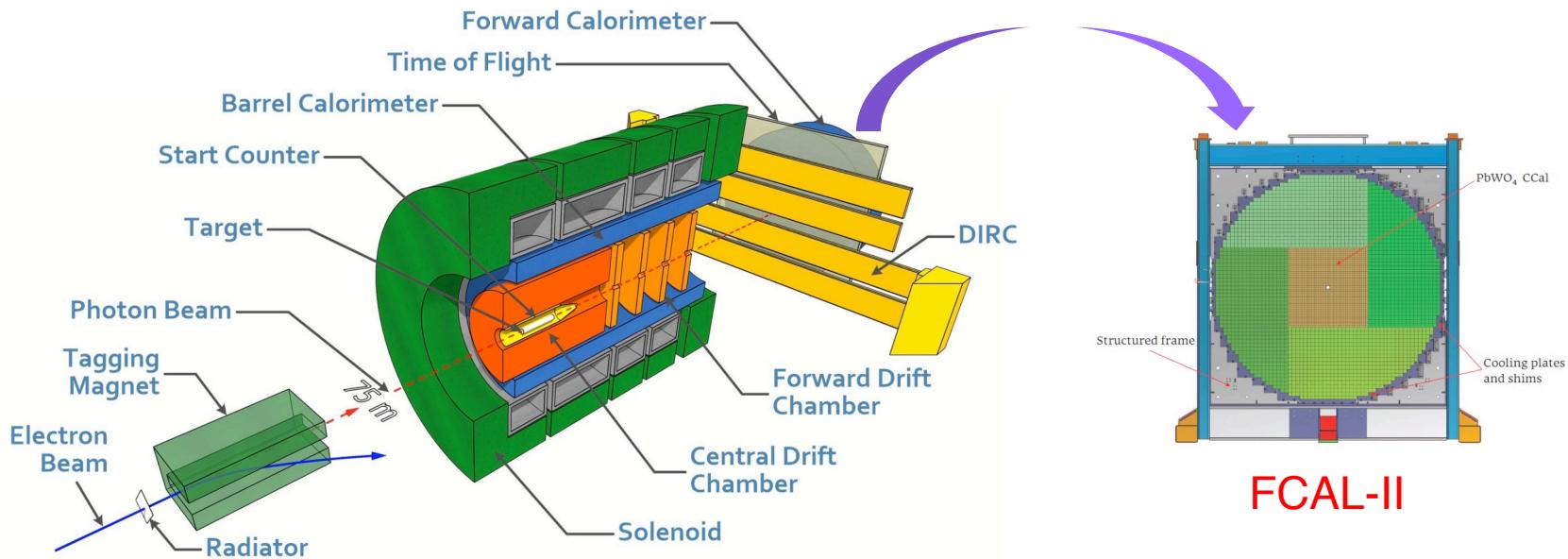
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BSM Physic Searches:

- Vector bosons (B boson, dark photon and X boson)
- Dark scalars
- Pseudoscalars (ALPs)
- BSM weak decays

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JLab Eta Factory (JEF) Experiment



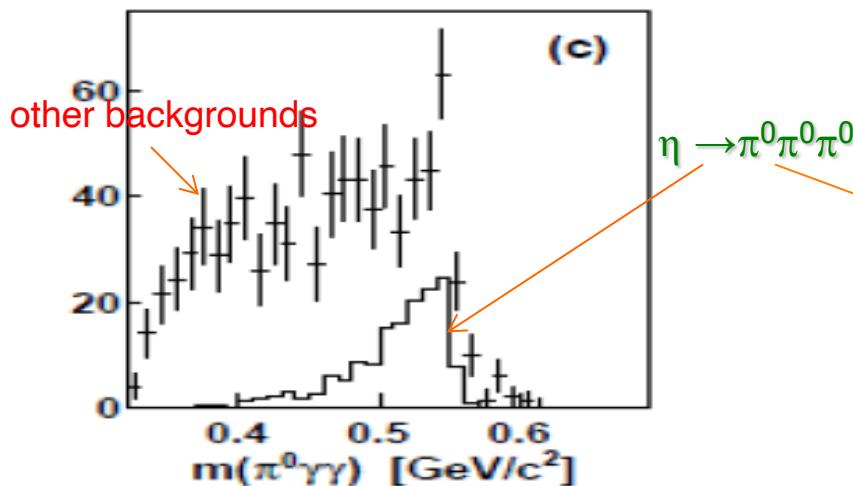
- ◆ Simultaneously produce η/η' on LH₂ target with **8.4-11.7 GeV tagged photon beam** via $\gamma+p \rightarrow \eta/\eta'+p$
- ◆ Reduce non-coplanar backgrounds by **detecting recoil protons** with GlueX detector
- ◆ Upgraded Forward Calorimeter with **High resolution, high granularity PWO** insertion (**FCAL-II**) to detect multi-photons from the η/η' decays
- ◆ The GlueX detector will detect the charged products from the η/η' decays

Uniqueness of JEF Experiment

1. Two orders of magnitude background suppression comparing to all other experiments:
 - a) η/η' energy boost; b) FCAL-II; c) exclusive detections

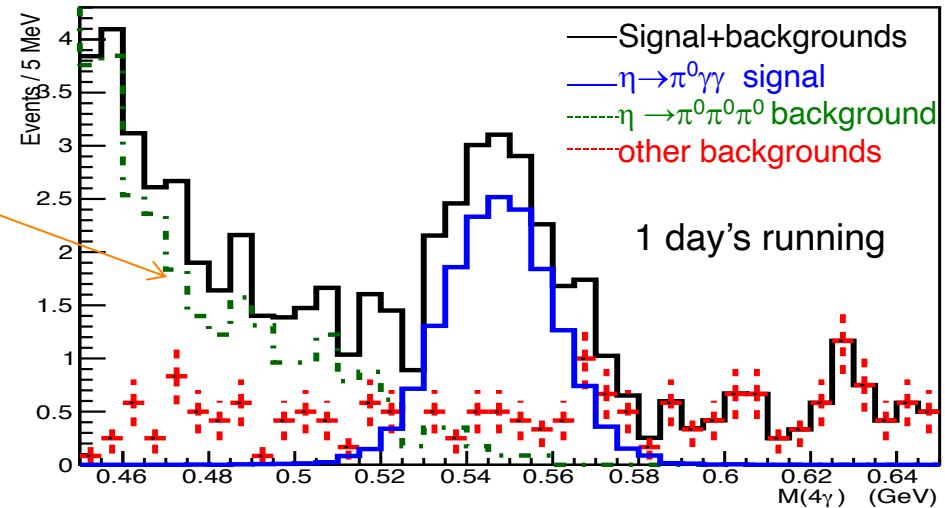
A2 at MAMI: $\gamma p \rightarrow \eta p$ ($E_\gamma = 1.5$ GeV)

(P.R. C90, 025206)



JEF: $\gamma p \rightarrow \eta p$ ($E_\gamma = 8.4-11.7$ GeV)

N (PWO) > 2



2. Capability of running in parallel with GlueX and other experiments in Hall D
→ high-statistics data set
3. Simultaneously produce tagged η and η' with similar rates (~ 5×10^7 per 100 days)

Production Rate

JEF for 100 days of beam:

	η	η'
Tagged mesons	6.5×10^7	4.9×10^7

Previous Experiments:

Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	10^6
WASA-COSY	$\sim 3 \times 10^7$ (p+d), $\sim 5 \times 10^8$ (p+p)	-
KLOE-II	3×10^8	5×10^5
BESIII	$\sim 10^7$	$\sim 5 \times 10^7$

JEF offers a competitive η/η' production rate with much less background

Main Physics Objectives

1. Search for sub-GeV hidden bosons

vector:

- Leptophobic vector B'
 $\eta, \eta' \rightarrow B'\gamma \rightarrow \pi^0\gamma\gamma$, ($0.14 < m_{B'} < 0.62$ GeV);
 $\eta' \rightarrow B'\gamma \rightarrow \pi^+\pi^-\pi^0\gamma$, ($0.62 < m_{B'} < 1$ GeV).
- X boson or dark photon: $\eta, \eta' \rightarrow X\gamma \rightarrow e^+e^-\gamma$.

scalar S: $\eta \rightarrow \pi^0S \rightarrow \pi^0\gamma\gamma, \pi^0e^+e^-$, (10 MeV $< m_S < 2m_\pi$);
 $\eta, \eta' \rightarrow \pi^0S \rightarrow 3\pi, \eta' \rightarrow \eta S \rightarrow \eta\pi\pi$, ($m_S > 2m_\pi$).

Axion-Like Particles (ALP): $\eta, \eta' \rightarrow \pi\pi a \rightarrow \pi\pi\gamma\gamma, \pi\pi e^+e^-$

2. Directly constrain CVPC new physics: $\eta^{(\prime)} \rightarrow 3\gamma, \eta^{(\prime)} \rightarrow 2\pi^0\gamma, \eta^{(\prime)} \rightarrow \pi^+\pi^-\pi^0$

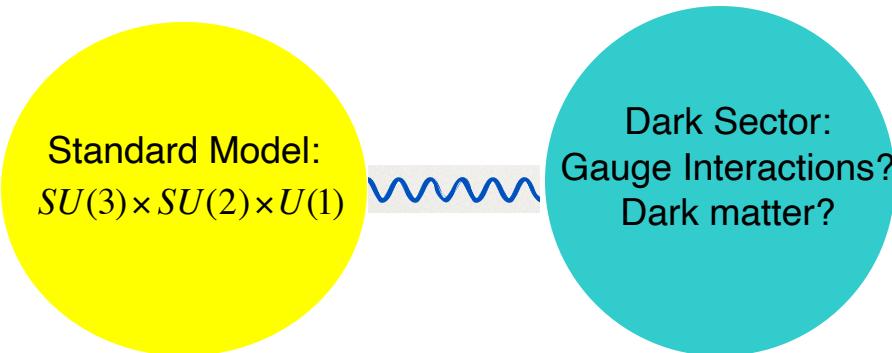
3. Precision tests of low-energy QCD:

- Interplay of VMD & scalar dynamics in ChPT: $\eta \rightarrow \pi^0\gamma\gamma$ $\eta' \rightarrow \pi^0\gamma\gamma$
- Inputs to calculate HLbL for $(g-2)_\mu$: $\eta^{(\prime)} \rightarrow e^+e^-\gamma$

4. Improve the quark mass ratio via $\eta \rightarrow 3\pi$

Example of a Key Channel: $\eta \rightarrow \pi^0 \gamma\gamma$

1. New physics:



Portal:	$(n = 4)$
vector	$\kappa B^{\mu\nu} V_{\mu\nu}$
Scalar	$H^+ H(\varepsilon S + \lambda S^2)$
fermion	ξLHN

❖ Search for sub-GeV gauge bosons

- A leptophobic **vector B' :**
 $\eta \rightarrow \gamma B'$, $B' \rightarrow \pi^0 \gamma$ PR,D89,114008
- An electrophobic **scalar Φ' :**
 $\eta \rightarrow \pi^0 \Phi'$, $\Phi' \rightarrow \gamma\gamma$

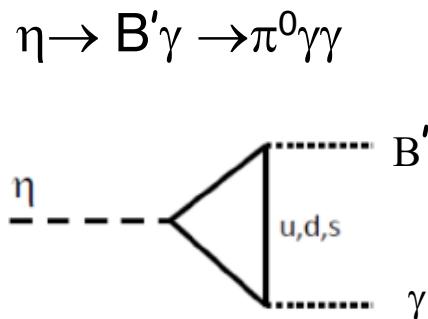
PRL 117,101801 (2016); PL B740,61(2015)

2. Confinement QCD:

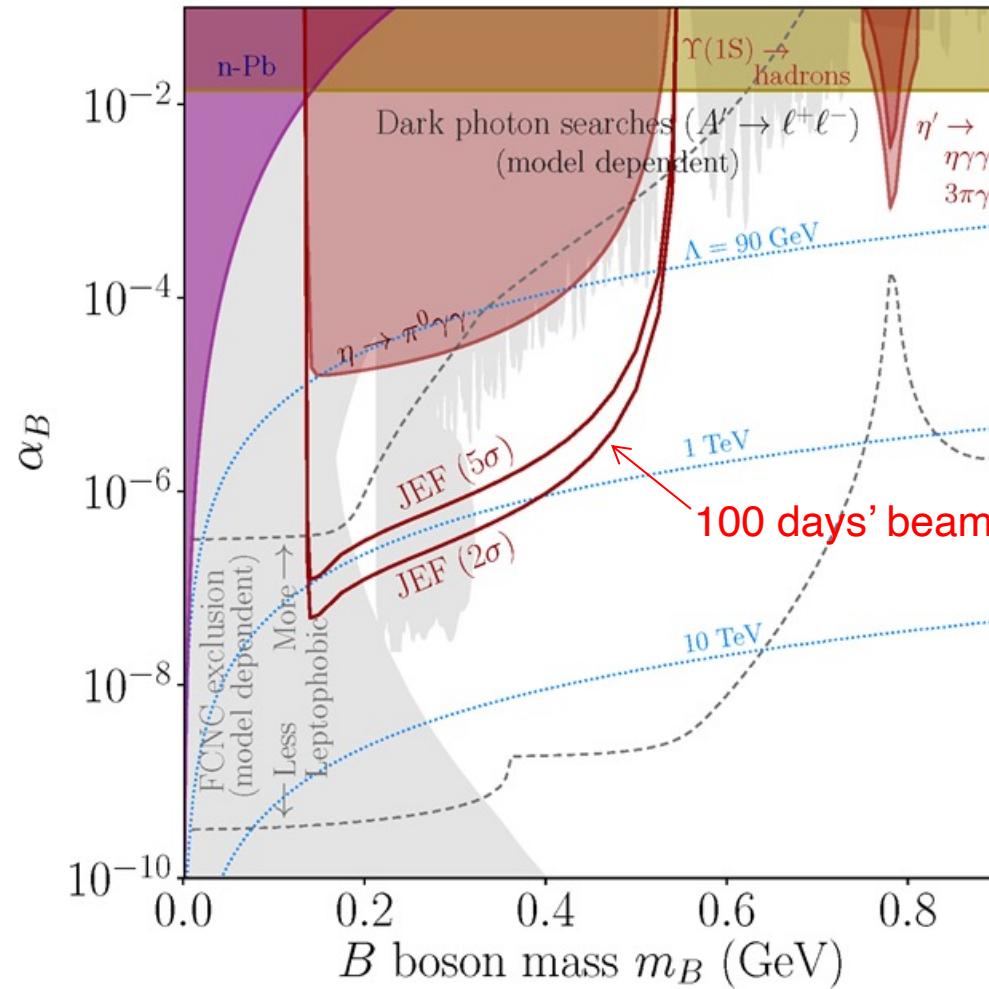
- ### ❖ A rare window to probe interplay of VMD & scalar resonance in ChPT

JEF Experimental Reach for B'

A search for a leptophobic dark B' boson coupled to baryon number is complementary to ongoing searches for a dark photon



PL, B221, 80 (1989)
PR, D89, 114008



Impact of the SM allowed $\eta \rightarrow \pi^0 \gamma \gamma$ measurement

- A rare window to probe interplay of VMD & scalar resonances in ChPT to calculate $O(p^6)$ LEC's in the chiral Lagrangian

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- A rare window to probe interplay of VMD & scalar resonances in ChPT to calculate $O(p^6)$ LEC's in the chiral Lagrangian
- ◆ The major contributions to $\eta \rightarrow \pi^0 \gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian → an unique probe for the high order ChPT.

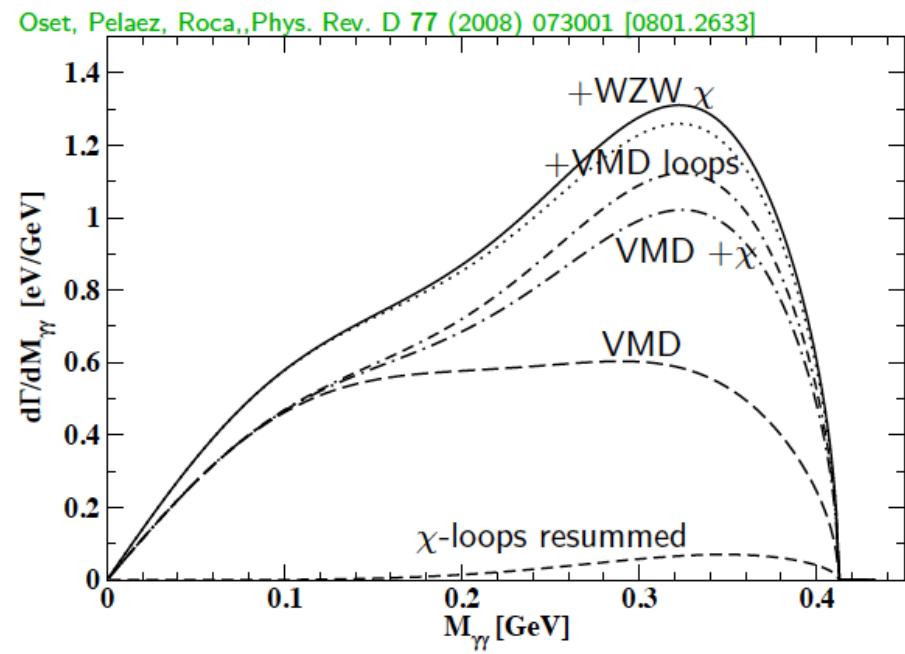
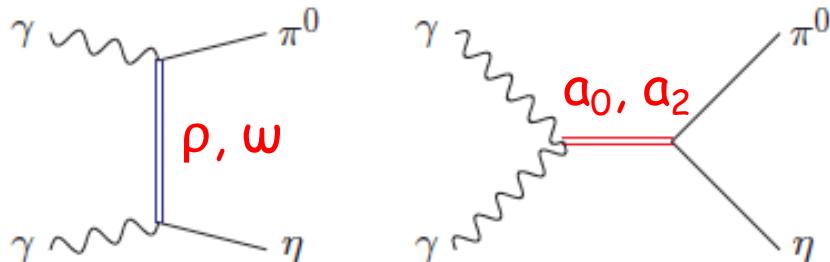
L. Ametller, J. Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

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L. Ametller, J. Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)
- ◆ Shape of Dalitz distribution is sensitive to the role of scalar resonances.

LEC's are dominated by resonances

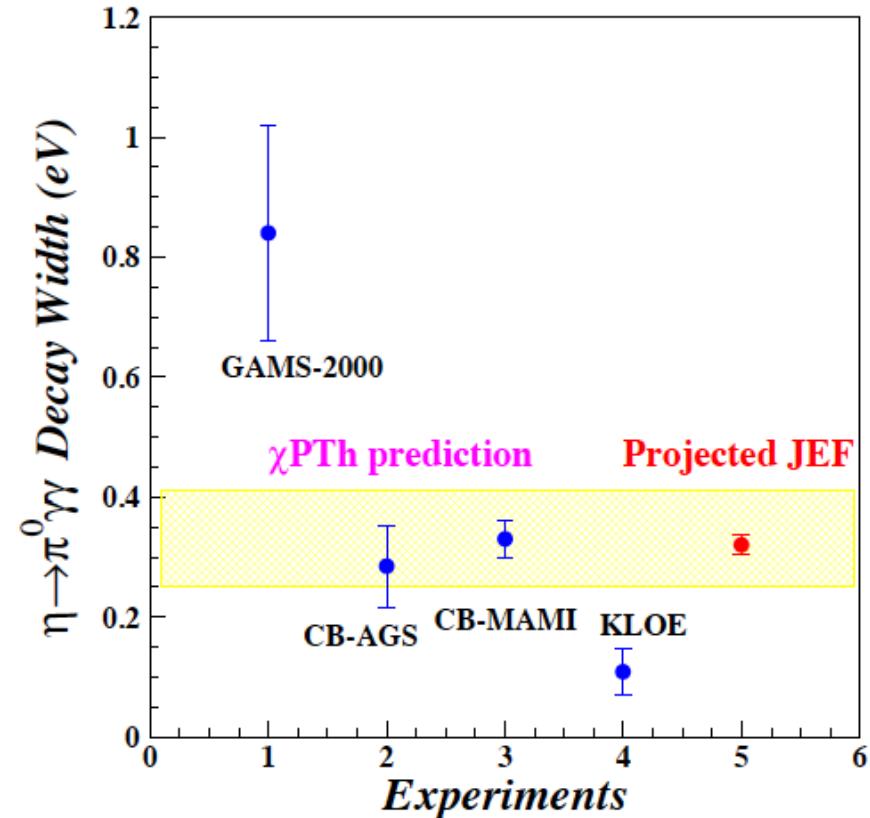
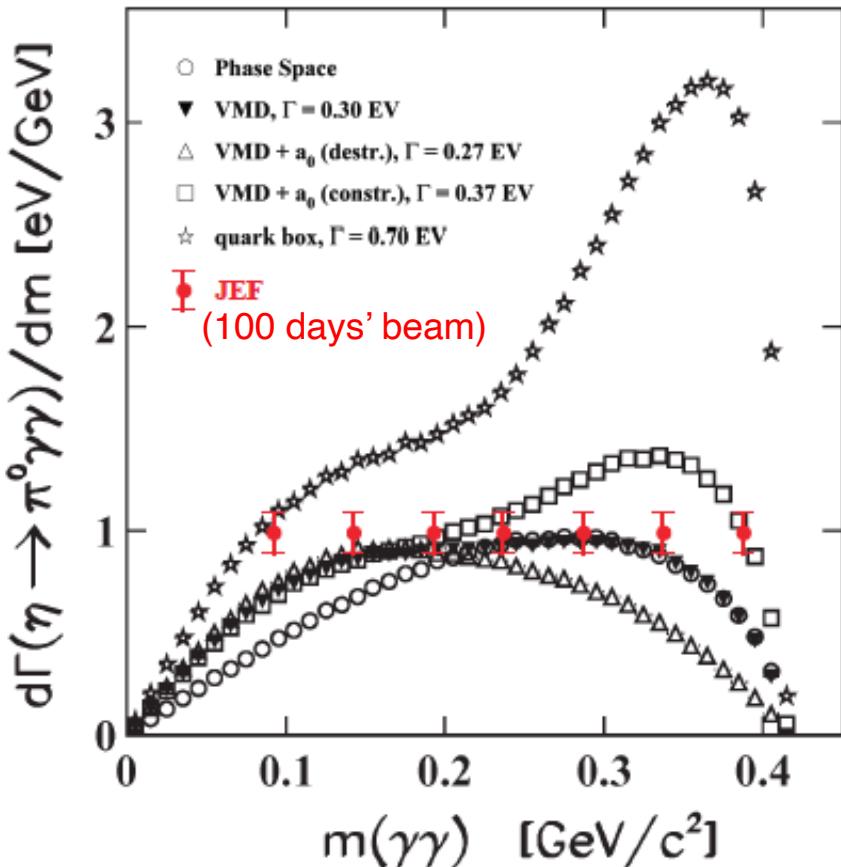
Gasser, Leutwyler 84; Ecker, Gasser, Pich, de Rafael 1989
Donoghue, Ramirez, Valencia 1989



Projected JEF on SM Allowed $\eta \rightarrow \pi^0 \gamma\gamma$

J.N. Ng and D.J. Peters, Phys. Rev. D47, 4939

χ PTh by Oset et al., Phys. Rev. D77, 073001



We measure both BR and Dalitz distribution

- ◆ model-independent determination of two LEC's of the $O(p^6)$ counter- terms
- ◆ probe the role of scalar resonances to calculate other unknown $O(p^6)$ LEC's

J. Bijnens, talk at AFCI workshop

Test Charge Conjugation Invariance

- ◆ C is maximally violated in the weak force and is well tested.
- ◆ Assumed in SM for electromagnetic and strong forces, but **it is not experimentally well tested**
(current direct constraint: $\Lambda \geq 1 \text{ GeV}$)

C Violating η neutral decays

Mode	Branching Ratio (upper limit)	No. γ 's
3γ	$< 1.6 \cdot 10^{-5}$	3
$\pi^0\gamma$	$< 9 \cdot 10^{-5}$	
$2\pi^0\gamma$	$< 5 \cdot 10^{-4}$	5
$3\gamma\pi^0$	Nothing published	
$3\pi^0\gamma$	$< 6 \cdot 10^{-5}$	7
$3\gamma 2\pi^0$	Nothing published	

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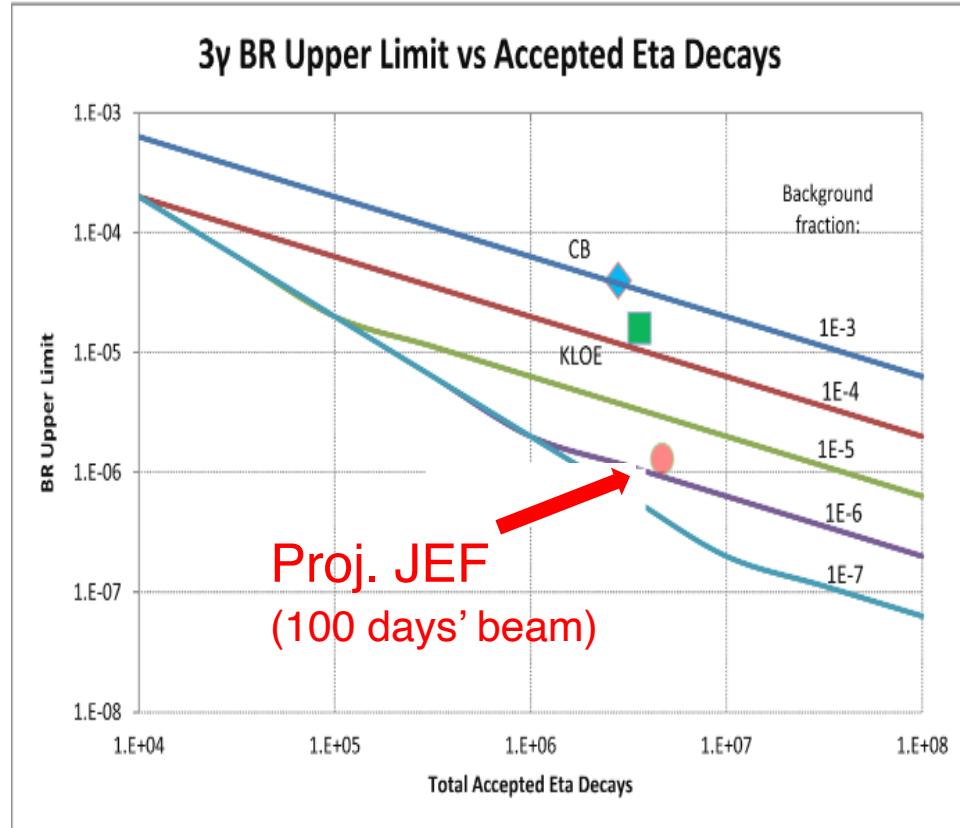
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Experimental Improvement on C-violating $\eta \rightarrow 3\gamma$

- ◆ SM contribution:
 $\text{BR}(\eta \rightarrow 3\gamma) < 10^{-19}$ via P-violating weak interaction.
- ◆ A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee
Phys. Rev., 139, B1650 (1965)
- ◆ A calculation due to such new physics by Tarasov suggests:
 $\text{BR}(\eta \rightarrow 3\gamma) < 10^{-2}$

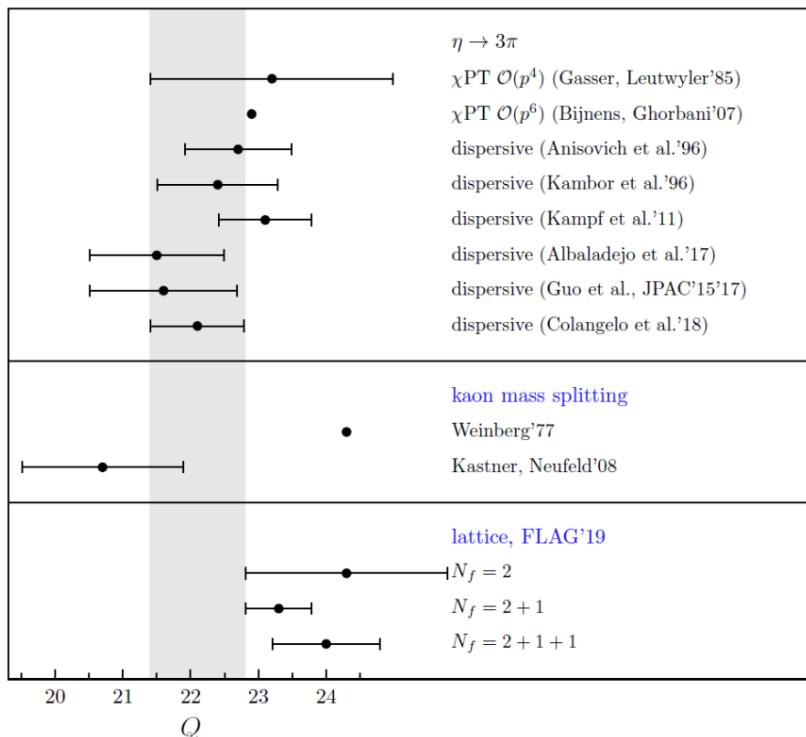


Sov.J.Nucl.Phys., 5, 445 (1967)

Improve BR upper limit by one order of magnitude to directly tighten the constraint on CVPC new physics

Improve Quark-Mass Ratio via $\eta \rightarrow 3\pi$

- ◆ A clean probe for quark mass ratio: $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\hat{m} = \frac{m_u + m_d}{2}$
 - Decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em}A_2$
 - α_{em} is small
 - Amplitude: $A(s, t, u) = \frac{1}{Q^2} \frac{m_K^2}{m_\pi^2} (m_\pi^2 - m_K^2) \frac{M(s, t, u)}{3\sqrt{3}F_\pi^2}$
 - ◆ JEF will improve the quark-mass ratio via measurement of $\eta \rightarrow 3\pi$ Dalitz distributions



Improve Quark-Mass Ratio via $\eta \rightarrow 3\pi$

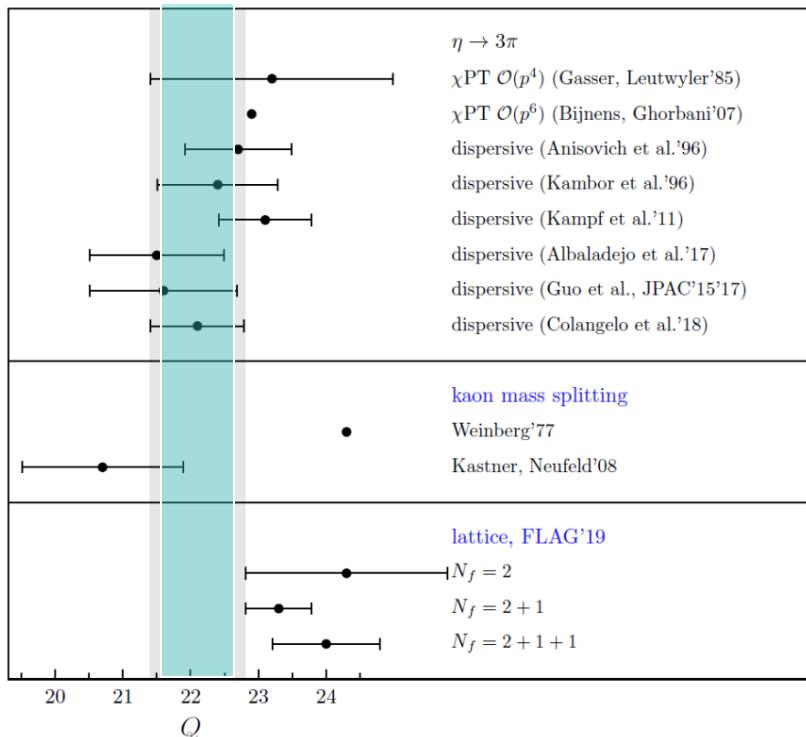
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➤ Amplitude: $A(s, t, u) = \frac{1}{Q^2} \frac{m_K^2}{m_\pi^2} (m_\pi^2 - m_K^2) \frac{M(s, t, u)}{3\sqrt{3}F_\pi^2}$

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Improve Quark-Mass Ratio via $\eta \rightarrow 3\pi$

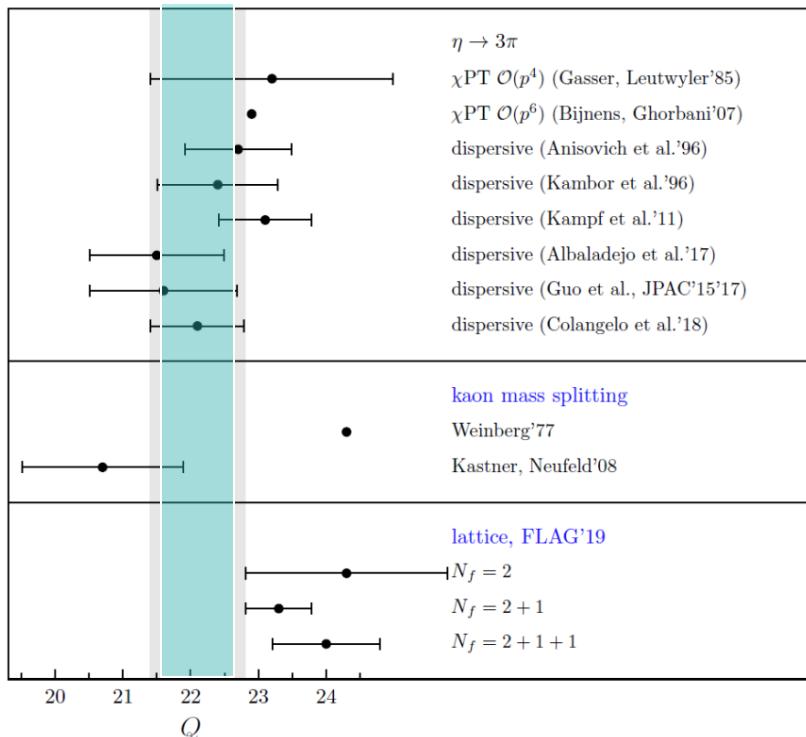
◆ A clean probe for quark mass ratio: $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\hat{m} = \frac{m_u + m_d}{2}$

➤ Decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em}A_2$

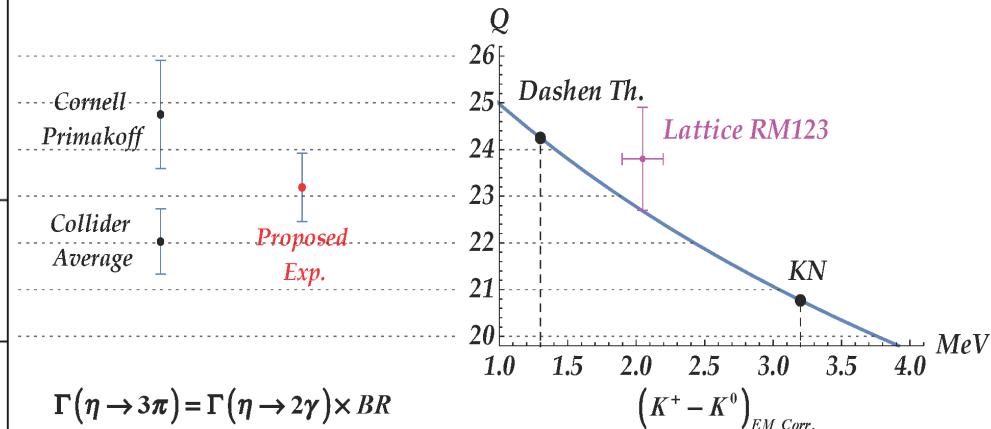
➤ α_{em} is small

➤ Amplitude: $A(s, t, u) = \frac{1}{Q^2} \frac{m_K^2}{m_\pi^2} (m_\pi^2 - m_K^2) \frac{M(s, t, u)}{3\sqrt{3}F_\pi^2}$

◆ JEF will improve the quark-mass ratio via measurement of $\eta \rightarrow 3\pi$ Dalitz distributions

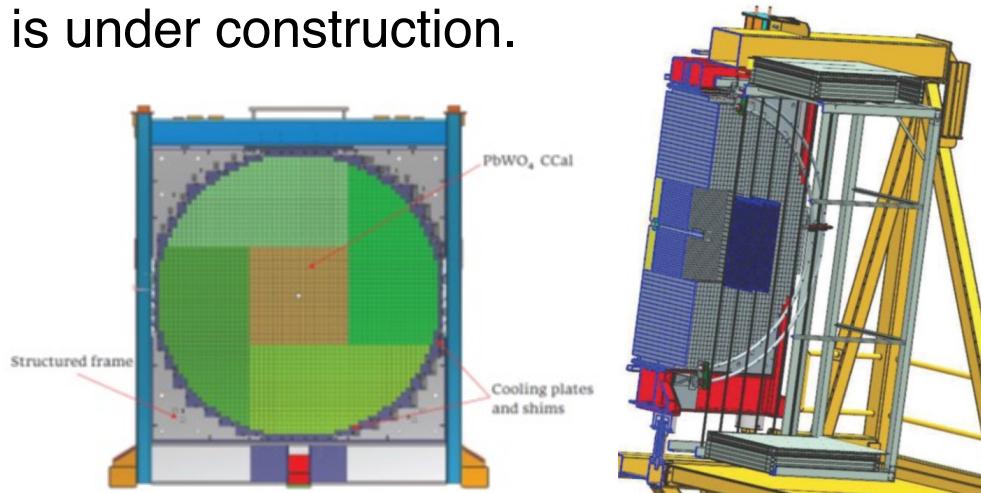


Further improvement by PrimEx-eta to measure $\Gamma(\eta \rightarrow \gamma\gamma)$

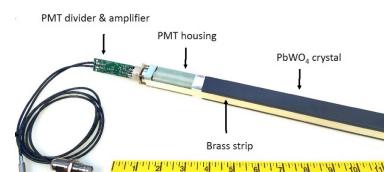


Current Status of the JEF Experiment

1. Non-rare decay data has been collecting with the GlueX spectrometer experiment since 2016.
2. A PWO insert to upgrade FCAL is under construction.
 - Mass production of 1600 PWO modules is on-going.
 - Engineering design for calorimeter frame is finalized.
 - Installation of the PWO insert is scheduled for 2023.
3. Rare decay data with FCAL-II is expected in 2024.
4. More beam time will be requested in 2023.



PWO module
(2x2x20 cm³)



Undergraduate workforce



Summary

- ◆ 12 GeV tagged photon beam with GlueX setup offers a unique η/η' factory to test SM and search for new BSM physics, with **two orders of magnitude in background reduction** in the neutral rare decay modes compared to other facilities.
- ◆ Simultaneously measure η/η' decays with main physics goals of:
 - Search for sub-GeV hidden bosons: vector, scalar, and ALP
 - Directly constrain CVPC new physics
 - Precision tests of low-energy QCD: the role of scalar dynamics in ChPT; transition form factors of η/η' to calculate HLbL contributions in $(g-2)_\mu$
 - Improve the light quark mass ratio via $\eta \rightarrow 3\pi$, $\eta' \rightarrow 3\pi$
- ◆ Data collection for non-rare decays has been on-going with the GlueX spectrometer experiment since 2016.
- ◆ The rare decays require an upgraded FCAL-II with a PWO insert that is currently under construction. Data taking will be expected in 2024.

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